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PETER J. DUNN
DAVID E. SMITH
RONALD KOLENKIEWICZ

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Peter J. Dunn
Wolf Research and Development Corporation
6801 Kenilworth Avenue
Riverdale, Maryland, U.S.A.

David E. Smith
Ronald Kolenkiewicz
Geodynamics Branch
Geodynamics Program Division
Goddard Space Flight Center
Greenbelt, Maryland, 20771

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ABSTRACT

New orbit computation techniques have been developed to realize the full precision of laser ranging measurements from a single tracking station used to accurately determine the orbital inclination of a satellite. In order to evaluate earth and ocean tidal effects on the satellite and polar motion effects on the station latitude, improved computational techniques are described for perturbations significantly influencing the satellite's inclination, such as solar radiation pressure and geopotential resonance. In conventional approaches to the analysis of long periodic effects, orbit timing errors caused by imprecise modelling of the gravity field and atmospheric drag often limit the orbital precision. By choosing the time-independent value of maximum latitude reached by the satellite as the experimental variable, this limitation has been largely overcome and made possible the long term analysis of osculating elements.[1] With these techniques, quarter day spans of laser data have been employed to monitor the inclination of the satellite to the order of 0.01 arcseconds precision over a period of seventeen months.

TECHNIQUES FOR THE ANALYSIS OF GEODYNAMIC EFFECTS USING LASER TRACKING DATA

INTRODUCTION

The contribution to the field of geodesy from highly precise laser range measurements to retro-reflector carrying satellites has been clearly demonstrated in recent years. Early applications of the laser data were in the fields of geopotential model recovery (Ref. 1) and station position estimation (Refs. 1, 2). In that work, the observations to several satellites from several lasers were incorporated in large-scale, multiple arc orbit determination systems in order to provide the solutions for geopotential coefficients or station locations with a scaling parameter. The capability of the laser information to define subtle variations in satellite and station position was only indirectly made use of in those applications.

In this paper, we describe a technique by which laser measurements may be used in an explicit definition of geodetic parameters at the one meter level of resolution. The observations made by a single tracking station (at NASA Goddard Space Flight Center) of a single satellite (Beacon Explorer C) have been analyzed with this technique to yield highly precise measures of perturbations to the satellite's inclination, including the effect of earth and ocean tides, and variations in the station's latitude, in particular the effect of polar motion. A detailed discussion of the results of the technique's application is presented in another paper (Ref. 3).

TRACKING CONFIGURATION

In June 1970, a Preliminary Polar Motion Experiment was initiated (Ref. 4), in which two laser systems (Ref. 5) gathered concentrated tracking data from the BEC satellite over a five month period. The goal of the experiment was to monitor the component of polar motion in the stations' common meridian through precise resolution of the inclination of the satellite, whose orbital characteristics are presented in Figure 1. Figure 1 also gives some important properties of the laser systems and the location of the tracking station at GSFC, whose latitude is within three degrees of BEC's inclination. In the post-experiment analysis, it was found (Ref. 6) that the concentration of observations from the GSFC site of the satellite's motion as it passed through the point of maximum latitude was sufficient to allow adequate inclination resolution with this station alone. As data from the International Satellite Geodesy Experiment became available, it was possible to extend the experimental period to approximately seventeen months. In order to employ data from a single station, however, certain requirements on data concentration must be met and a technique to separate cross-track orbit error from along-track error effects had to be developed.

SATELLITE BEC

KEPLERIAN ELEMENTS ON JUNE 17, 1970:			
	SEMI–MAJOR AXIS		7510 Km.
	ECCENTRICITY		0.025
	INCLINATION		41.2°
	PERIGEE HEIGHT		950 Km.
	APOGEE HEIGHT		1320 Km.
	NODE RATE		-4.2°/day
	ARGUMENT OF PERIGEE RATE		5.2°/day
	PERIOD		108 min.
	AREA		1.25 m^2.
	MASS		53 Kg.
STATION GSFC			
	LATITUDE	LONGITUDE	HEIGHT
	$39^{\circ}01'13.88''$	$283^{\circ}10'18.50''$	9.29 m.
PULSE ENERGY		1 JOULE	
REPETITION RATE		1 SEC^{-1}	
NOISE LEVEL		30–50 CM.	

Figure 1. Satellite and Station Characteristics

BASIC TECHNIQUE

Precise measurements of the satellite's osculating inclination may be obtained, based on observations gathered over a relatively short period of approximately six hours, using a weighted least squares orbit determination method (Ref. 7). These measurements can then be compared with inclination values of a reference orbit generated with the same dynamic model but extending over the full experimental period. The signature of the differences between the short-arc determined inclinations and those of the reference orbit may then be analyzed to identify errors in the model affecting the inclination of the reference orbit, and the significant effects are described below.

If the short-arc inclinations are compared with the reference orbit inclinations at the same time, the satellite positions are seen to be at a considerable distance apart (several hundred kilometers in seventeen months) at the comparison points. In particular, the positions are at different latitudes, which degrades the inclination resolution. This is due to the effect of errors in the atmospheric drag model used (Ref. 8) and the geopotential model (Ref. 9) which result in large along-track position errors. However, by comparing osculating inclinations at equivalent points in space (at the positions of the maximum latitude reached in each orbit) the effect of along-track error on cross-track resolution is reduced to the extent that inclination precision at the meter level can be obtained.

SHORT ARC ORBIT RESOLUTION

The maximum number of passes observable on consecutive revolutions of BEC from GSFC is five. In general, however, operational constraints limit the number of consecutive passes. During the seventeen month period considered here, at least four consecutive passes were obtained on thirty-six occasions (on only one of these occasions was the theoretical maximum of five passes realized). Figure 2 shows the groundtrack of a typical quadruple pass situation on Sept. 2, 1970 as the GSFC station rotates below the satellite orbit. The laser can observe the satellite trajectory as it passes through the point of maximum latitude on two separate revolutions.

In order to determine the minimum number of consecutive passes of range data that must be taken to adequately resolve the satellite's inclination, an error analysis was performed. An orbital error analysis technique (Ref. 10) was employed to compute the sensitivity to dynamic, station and measurement errors of the cross-track orbit position at the point of maximum latitude, as determined by five typical short-arc configurations. Gravity model error was represented by 25% of the difference between two full geopotential models (Refs. 11 and 12). This measure of gravity error was derived (Ref. 13) for the SAO 1969 Standard Earth (Ref. 1) but was used in the error analysis as an approximate general measure for any gravity model.

The results of the error analysis study are shown in Figure 3, which presents the variation in inclination resolution given by the five sample configurations assuming the number of consecutive passes available was between two and five. An observed systematic dependence on pass geometry is not shown in Figure 3, which nonetheless suggests that at least four consecutive passes of data must be used to reduce the effects of rather pessimistic assumed model error to the meter level. Interpretation of the effects of geopotential model error must be qualified by the expected partial cancelling of this error source when the inclinations of the reference orbit are differenced with those of the short-arc orbits.

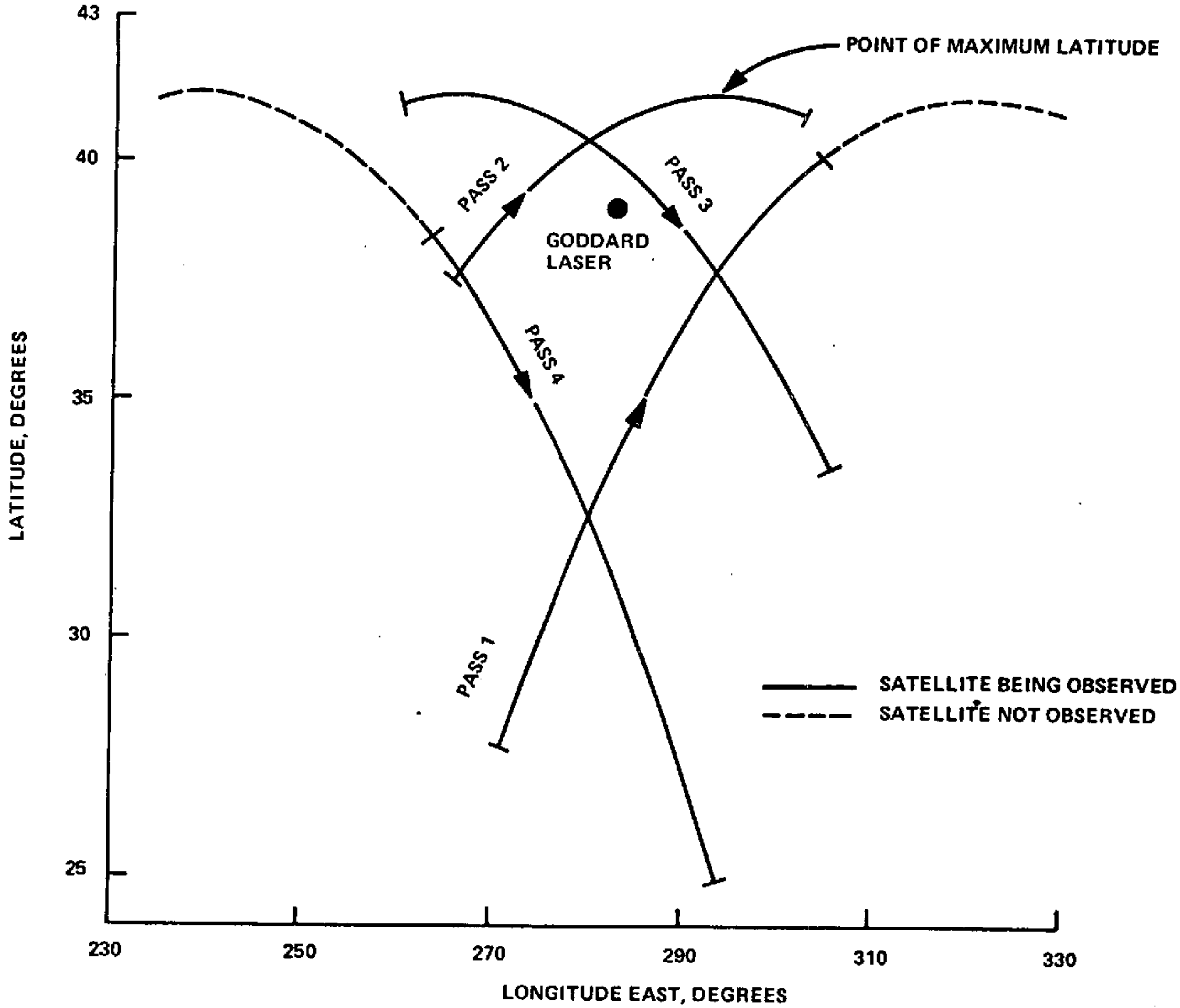

Figure 2. A Typical BE-C Groundtrack

NUMBER OF PASSES	VARIATION IN CROSS-TRACK POSITION (METERS) DUE TO ERROR IN: GRAVITY	$GM(10^{-6})$	REFRACTION (10%)	STATION HEIGHT (5 m.)	RANGE BIAS (50 cm.)
2	3.5	10.5	5.1	10.6	4.0
3	39.4	7.8	4.7	7.6	3.0
4	5.6	1.1	0.7	0.9	0.5
5	2.9	1.1	1.7	0.4	0.5

Figure 3. Effect of Model Errors on Inclination Resolution for Five Short Arcs

REFERENCE ORBIT PRECISION

The 6-hourly values of inclination determined using short arcs of four consecutive passes of range data are relatively insensitive to inclusion in the model of the dynamic effects on the satellite which it is our aim to monitor. The representation of the station-dependent effect of polar motion in the model is however critical in the estimation of the short-arc inclinations. A reference orbit which extends over the full seventeen month experimental period will provide sensitivity to long-period effects on the inclination caused by dynamic model error. This reference orbit is obtained by extrapolating an orbit determined using a subset of our seventeen month data span. Approximately three weeks of data available during a concentrated tracking period in August 1970 have been found to yield reference orbits whose integrity is maintained under extrapolation over the experimental time span.

The short arc inclinations may be compared with those defined by the reference orbit, each value taken at the point of maximum latitude reached in its respective orbit. In Figure 4, the results of this comparison are shown for each pass of a typical four-pass arc. The short arc inclination values follow those given by the reference orbit but are offset by an amount which should remain constant over the seventeen month period and depends on the inclination chosen to initiate the reference orbit.

INCLINATION PERTURBATIONS

The direct luni-solar effects produce a variation in BEC's inclination amounting to approximately 35 arcseconds. It has been assumed in our analysis that this direct effect has been modeled with no error. The effect on the satellite inclination of earth and ocean tides whose disturbing potential is represented by two second degree spherical harmonics aligned in the general directions of the sun and moon, is shown in Figure 5. The size of the inclination variation produced on BEC amounts to approximately 2 arcseconds if the ratio of the tidal

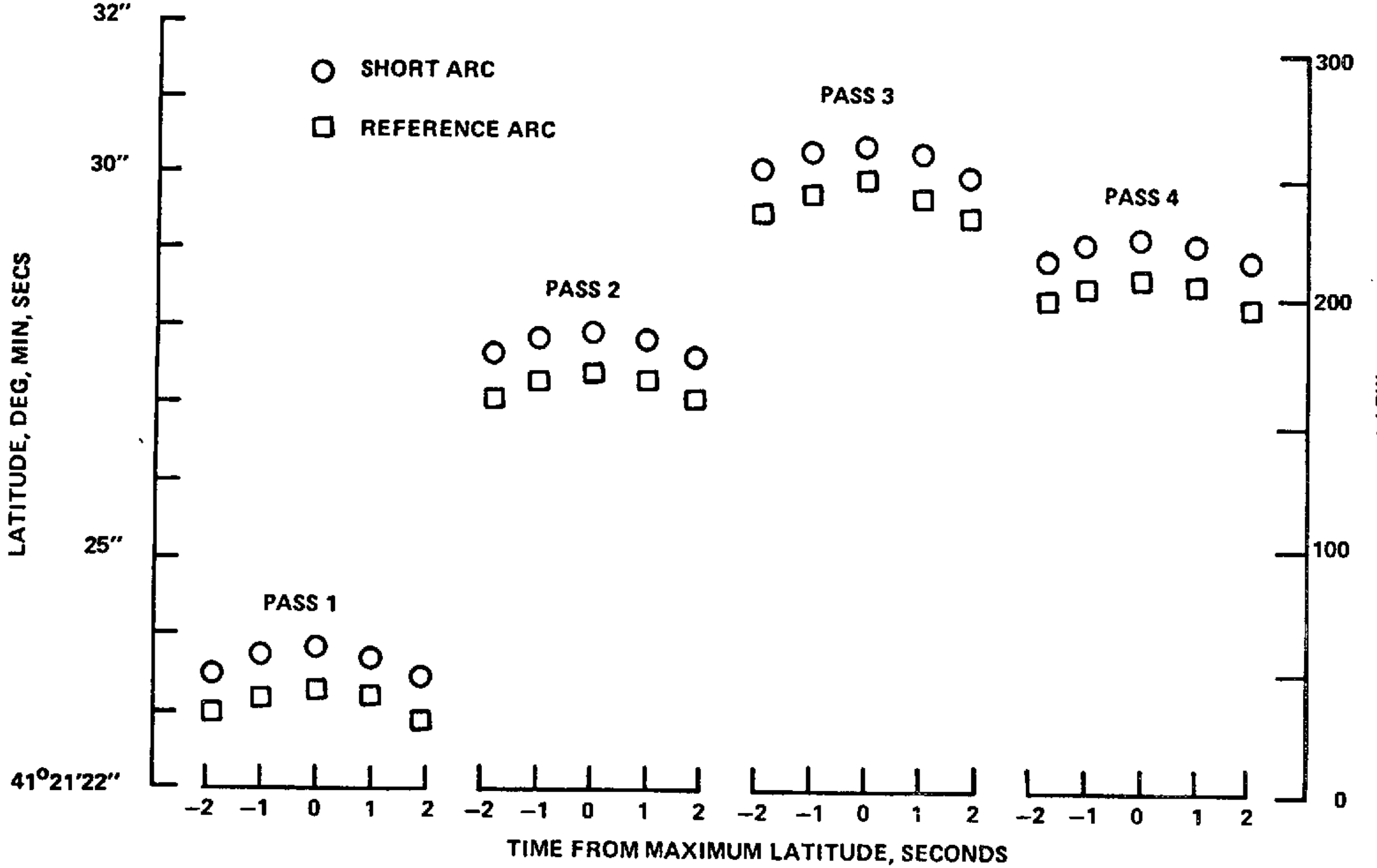

Figure 4. Maximum Latitudes for a Typical Godlas Arc

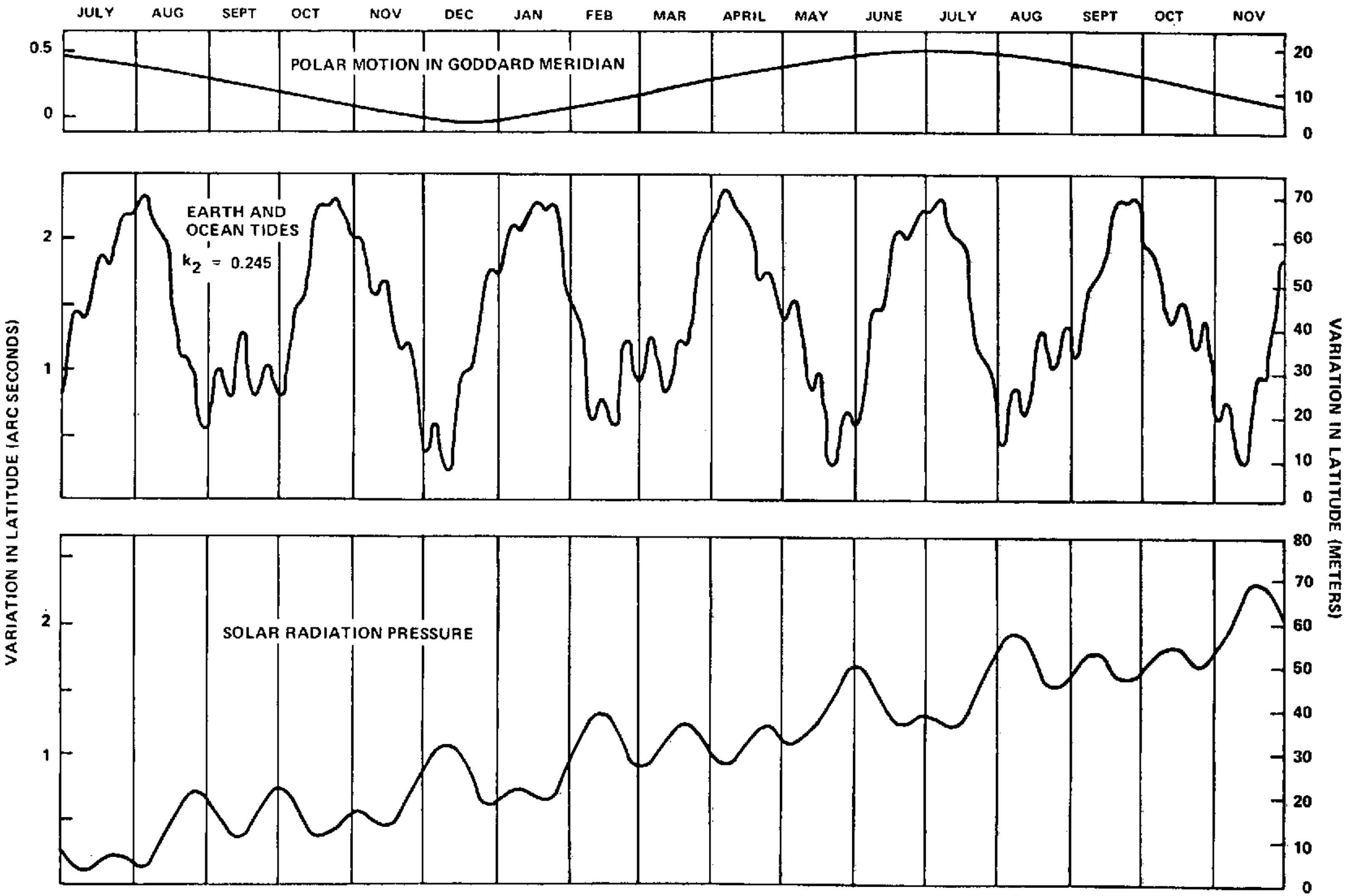

Figure 5. Large Inclination Perturbations

potential to the tide rising potential is 0.245. The signature of the inclination variation is similar to that due to the direct luni-solar effect and contains a period of 85 days, the nodal period of BEC, and periods of 34 and 10 days, corresponding to half the rotation periods of the orbit plane with respect to the sun and moon respectively.

The secular effect on the satellite's inclination due to solar radiation pressure is also shown in Figure 5 to amount to about 2 arcseconds over the seventeen month period. This secular growth is modulated by a term of 35 days, which is half the period of perigee rotation for BEC. In order to accurately model the solar radiation pressure effect, the instantaneous satellite area exposed to solar radiation must be precisely computed. As BEC is magnetically stabilized a simple magnetic field model was constructed and used in conjunction with an expression (Ref. 14) for the exposed satellite area as a function of the angle between the line to the sun and the symmetry axis of the satellite.

Figure 5 also shows the effect on the short-arc inclination measurements of the component of polar motion (Ref. 15) in the GSFC station's meridian during the period of the experiment. To provide a scale comparison, this effect is reproduced in Figure 6, which also shows the effects of some more subtle inclination perturbations. If the phase lag in the tidal response of the earth is represented as an off-set of 2.5° in the angle between the earth's centre and the tide-rising bodies, the corresponding inclination effect is shown in Figure 6. The variation amounts to approximately 0.1 arcseconds over the seventeen month period and is only shown for the first five months in the figure.

The BEC orbit has a period of approximately thirteen revolutions per day and is thus resonant with geopotential terms of order thirteen. The effect on inclination of a 20% error in the value of a dominant resonance term (C,S (19, 13)) in the geopotential model (Ref. 9) chosen for the experiment is shown in Figure 6. The period of this resonance signature is 5.54 days and the magnitude of the resonance effect on the inclination is similar to that of a 2.5° phase lag..

Figure 6 finally displays the residuals of 6-hourly inclination measurements to those of a reference orbit generated using an optimum combination of values for the ratio of tidal potential to tide rising potential, phase lag angle and a geopotential term C, S (19, 13) adjusted to absorb errors in the resonance model for BEC. The root mean square inclination fit of less than 0.05 arcseconds demonstrates the precision of the technique when applied with the finally chosen model. The signatures of the effects whose magnitudes were estimated are shown in Figures 5 and 6 to be completely different from each other and from major inclination perturbations due to solar radiation pressure and polar motion, which were not adjusted. The considered inclination perturbations can therefore be easily separated and their estimated magnitudes will be precise (Ref. 3).

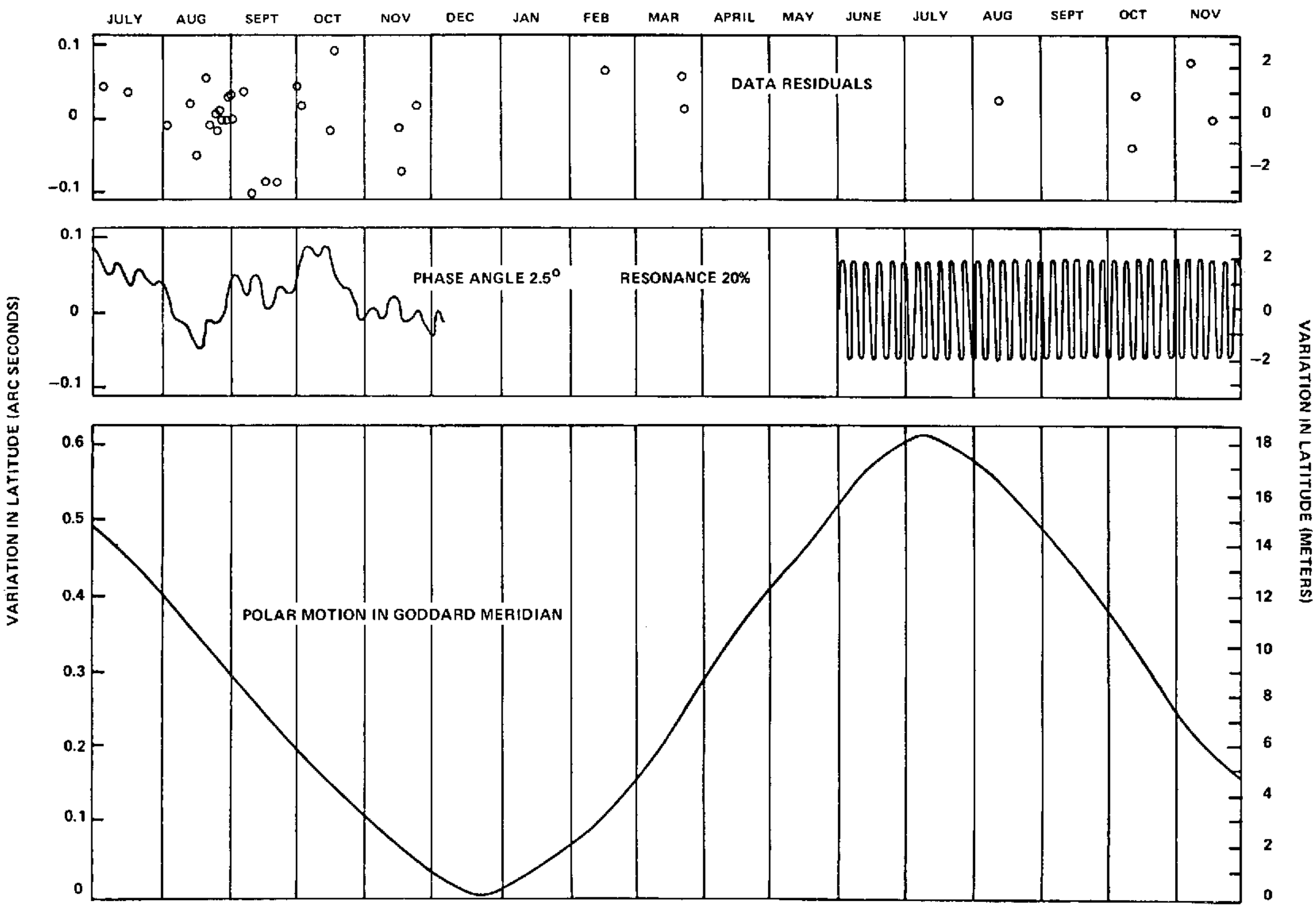

Figure 6. Small Inclination Perturbations

CONCLUSIONS

The accuracy and precision of the Goddard laser systems are presently undergoing considerable improvement (Ref. 16). However, the 30-50 cm. noise of the range measurements used in this analysis appears to be a less significant constraint on the precision of the results than dynamic model error, particularly in the representation of the geopotential. We therefore suggest that a single laser system which produces a reasonable concentration of range measurements at the one meter noise level and is free of long-term bias can yield results of geodetic significance if some consideration is given to the technique of data analysis.

REFERENCES

1. Gaposchkin, E.M., and K. Lambeck, "1969 Smithsonian Standard Earth," S.A.O. Spec. Rep. 315, May 18, 1970.

2. Marsh, J.G., B.C. Douglas and C.F. Martin, "NASA STADAN, SPEOPT and Laser Tracking Station Positions derived from GEOS-1 and 2 Precision Reduced Optical and Laser Observations," Space Res., 12, 507-514, 1971.

3. Kolenkiewicz, R., D.E. Smith and P.J. Dunn, "Polar Motion and Earth Tides from Beacon Explorer C," First Int. Symp. on Use of Art. Sat. for Geodesy and Geodynamics, Athens, May 1973.

4. Smith, D.E., R. Kolenkiewicz and P.J. Dunn, "Geodetic Studies by Laser Ranging to Satellites," Geophys. Mon. Series Vol. 15, 187-196, 1972.

5. Johnson, T.C., H.H. Plotkin and P.L. Spadin, "A Laser Satellite Ranging System, 1, Equipment Description," I.E.E.E. J. Quantum Electronics, QE-3(11), 435-439, 1967.

6. Smith, D.E., et al., "Polar Motion from Laser Tracking of Artificial Satellites," Science Vol. 178, 405-406, Oct. 1972.

7. Martin, T.V., "GEODYN Descriptive Summary," G.S.F.C. Contract Report NAS 5-11735-05, Wolf Research and Development Corp., Riverdale, Maryland, Sept. 1972.

8. Jacchia, L.G., "The Upper Atmosphere," Phil. Trans. Royal Soc., Vol. 262, 1967.

9. Smith, D.E., F.J. Lerch and C.A. Wagner, "A Gravitational Field Model for the Earth," Space Research 13, Akademie-Verlag, Berlin, 1973.

10. Martin, C.F., "Error Analysis of Statistical Techniques Used in Orbit Estimation," Wolf Research and Development Corp., Tech. Report, June 1969.

11. Gaposchkin, E.M., S.A.O. Spec. Report 200, Vol. 2, 1966.

12. Guier, W.H., and R.R. Newton, "The Earth's Gravitational Field as Deduced from the Doppler Tracking of Five Satellites," J. Geophys. Res., 70(18), 4613-4626, 1965.

13. Martin, C.F. and N.A. Roy, "Error Model for the SAO 1969 Standard Earth," Geophys. Mon. Series Vol. 15, 161-167, 1972.

14. Safren, H., G.S.F.C., private communication, 1972.

15. Guinot, B., M. Feissel and M. Granveaud, "Annual Report for 1970/71," Bureau International de l'Heure, Paris, 1971/72.

16. Plotkin, H.H., T.S. Johnson and P.O. Minott, "Progress in Laser Ranging to Satellites: Achievements and Plans," First Int. Symp. on Use of Art. Sat. for Geodesy and Geodynamics, Athens, May 1973.